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Numerical and experimental study of a plate-stiffened prismatic pressure vessel

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A B S T R A C T

This study evaluates the structural feasibility of a prismatic pressure vessel using strength assessments. A prismatic pressure vessel, which differs from a cylindrical or spherical pressure vessel, is proposed. A prismatic pressure vessel can be used to ship liquefied gas. A prototype of the prismatic pressure vessel was designed, manufactured and tested in accordance with the ASME Boiler and Pressure Vessel Code. Its design uses the "design-by-analysis" method, including protection against plastic collapse. The prototype of the prismatic pressure vessel uses typical construction materials considering their linear elastic and nonlinear plastic behaviors. The vulnerable components of the structure were obtained through numerical analysis using the finite element method. A pressure test with strain gauges was conducted, and the results demonstrate the feasibility of the prismatic pressure vessel as a suitable vessel for high-pressure fluids with high volume efficiencies. The prismatic pressure vessel has potential for general applicability in the shipping of liquefied gas.

1. Introduction

Recently, the demand for liquefied gas propulsion technology has increased, driven by the strengthening of IMO regulations for clean shipping in 2014 (DNV, 2011). To achieve gas-fueled propulsion, one essential challenge is the type of fuel tanks that can be used. Several types of fuel storage tanks are available, including membrane tanks or independent tanks, e.g., IMO type-A, -B, and -C tanks (IMO, 2008, 2009). Tanks other than IMO type-C tanks may need additional equipment to address the boil-off gas from liquefied gases due to external heat ingress in a gas-fueled ship.

Generally, a conventional pressure vessel is designed using a complete cylinder and dish-ends, which constrains its installation on an open deck or inside a hull because dead space is created between the vessel and the hull. All space on any ship is of significant value. A user or owner of a merchant ship with gas-fueled propulsion may require more liquefied gas to be contained in a storage tank. A storage tank shape that conforms to the hull with a high-volume efficiency and a pressure that exceeds atmospheric pressure can satisfy the user's requirements (Ahn et al., 2017; Lee et al., 2017).

A prismatic pressure vessel can be an alternative solution to these challenges. This tank is classified as an IMO type-C tank and can contain a relatively high pressure with high volume efficiency. Such a tank is normally manufactured as a modular extension of a structural component in any spatial direction and easily adapts to any size because of its repeated pattern. Its principal component is a beam structure or parallel plate structure, which acts as a load-bearing system (Ahn, 2012; Chang and Bergan, 2012; Choi, 2016).

In the design of prismatic pressure vessels, relevant design regulations must be considered. For ship applications, IMO published the IGC code (IMO, 2008) and promulgates several requirements, including MSC.285 (86) (IMO, 2009). Although MSC.285 (86) is currently undergoing revisions, this standard has provided an interim guideline for gas-fueled ships since 2009. Most requirements are presented in the IGC code, which contains the requirements for the design, manufacture, commissioning, and operation of all equipment for liquefied gas carriers. In particular, regarding pressure vessels, the IGC code describes a generally acceptable design theory that may be used; the theory is accepted by standards such as EN 13458 and the ASME Boiler and Pressure Vessel Code (hereafter, the ASME code).

Section VIII of the ASME code specifies three divisions: Division 1 – Rules for the Construction of Pressure Vessels, Division 2 – Alternative Rules for the Construction of Pressure Vessels and Division 3 – Alternative Rules for the Construction of High-Pressure

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Nomenclature

A	cross-sectional area of a parallel plate
a	length of plate edge 1
b	length of plate edge 2
t_i	thickness of i (i = pp (parallel plate), p (plate), sx (x-stiffener), sy (y-stiffener))
n_i	number of parallel plates in the i-direction (i = x, y)
n_{si}	number of stiffeners in the i-direction (i = x, y)
σ	tensile stress of external plate
σ_a	allowable stress
σ_{cr}	critical buckling stress
m	summation constant for deflection
n	summation constant for deflection
p	plate internal pressure
N_x	compressive force
w	internal parallel plate deflection
E_i	Young's modulus in the i-direction (i = x, y)
ν_i	Poisson's ratio in the i-direction (i = x, y)
k	buckling coefficient
σ_i	stress in the i-direction (i = x, y, xy)
ε_i	strain in the i-direction (i = x, y, xy)
γ	shear strain
G_{xy}	shear modulus
D_i	flexural rigidity in the i-direction (i = x, y, xy)
D_t	torsional rigidity
m_i	bending moment per unit length in the i-direction (i = x, y)
m_{xy}	twisting moment per unit length
h_{si}	stiffener height in the i-direction (i = x, y)
B	effective torsional rigidity of an orthotropic plate
s_i	spacing in the i-direction (i = x, y)
z_i	length between the neutral axis of an external plate and a stiffener in the i-direction (i = x, y)
I_i	moment of inertia in the i-direction (i = x, y)
P_m	primary general membrane stress
P_L	primary local membrane stress
P_b	primary bending stress
S	allowable stress of the material
Barg	unit of gauge pressure
ASME	American Society of Mechanical Engineers
ISO	International Organization for Standardization
IMO	International Maritime Organization
MSC	Maritime Safety Committee
IGC	International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
MAWP	Maximum Allowable Working Pressure
ASTM	American Society for Testing and Materials
FEM	Finite Element Method
LSR	smallest ratio of the allowable stress at test temperature to the allowable stress at the design temperature of materials used in vessel construction

Vessels. Division 1 consists of material selection, the design and construction of pressure vessels for generally known shapes. Division 3 involves rules for pressure vessels that can withstand high pressures above 10 ksi (70 MPa). Specifically, Division 2 addresses a pressure vessel for on-board transport, a non-circular vessel (ASME, 2010a). This division is applicable for the design of an on-board pressure vessel for gas fuel storage. Division 1 adopts a relatively simple calculation with an approximation formula, and the design and requirements for stress analysis are described through complex calculation methods. In Division 2, there are two different methods of designing pressure vessels: design by rule and design by analysis. Design by rule provides "design rules for commonly used pressure vessel shapes under loading within specified limits, rules or guidance for the treatment of other loadings". Design by rule does not provide all load conditions and geometries. Therefore, in the case of pressure vessels not covered by the design by rule strategy, design by analysis is applied (Desai and Patel, 2014; Stonehouse et al, 2012; Slagis, 2005).

Otherwise, the rules of classification groups are based on the IGC code. These rules are applicable to a conventional pressure vessel but not to a prismatic pressure vessel. Thus, they cover only conventional pressure vessels (ABS, 2010; DNV, 2013; GL, 2008).

This study includes a strength assessment of a prismatic pressure vessel with plate structures based on numerical and experimental stress analyses. The main purpose of manufacturing a prototype vessel is to evaluate the design concept, manufacturability, and use of a hydrostatic pressure test. These considerations satisfy the ASME code for approval by a third-party authorized inspection (ASME, 2010a; Desai and Patel, 2014; Mohite Suraj and Kotwal Girish, 2017).

Section 2 presents the design principle of the prismatic pressure vessel. Section 3 provides the configuration of the prototype, construction materials, and design considerations of the prismatic pressure vessel. Section 4 presents the procedure and results of the strength calculation by numerical analysis using the finite-element method. Section 5 discusses the experimental stress analysis results using strain gauges, which indicate that the design concept of the prismatic pressure vessel is feasible for containing pressurized liquids. Section 6 summarizes and concludes this paper.

2. Design principle of a plate-stiffened prismatic pressure vessel

The basic principle of the plate-stiffened prismatic pressure vessel is as follows. In the design, we use a combination of three design principles. First, to design the parallel plate, we check the force equilibrium when internal pressure is applied. Second, we verify two conditions: whether the parallel plate can withstand the weight of the upper part of the pressure vessel and whether buckling occurs. Finally, it is confirmed that the stiffener installed outside the pressure vessel can withstand the internal pressure.

2.1. Parallel plate thickness calculation

Fig. 1 shows the equilibrium of the force of the tensile stress on the internal parallel plate due to the internal pressure that initially acts on the external plate.

When there are n_x parallel plates in the x-direction, n_y parallel plates in the y-directions, and the plate thickness is t_{pp}, the total area is

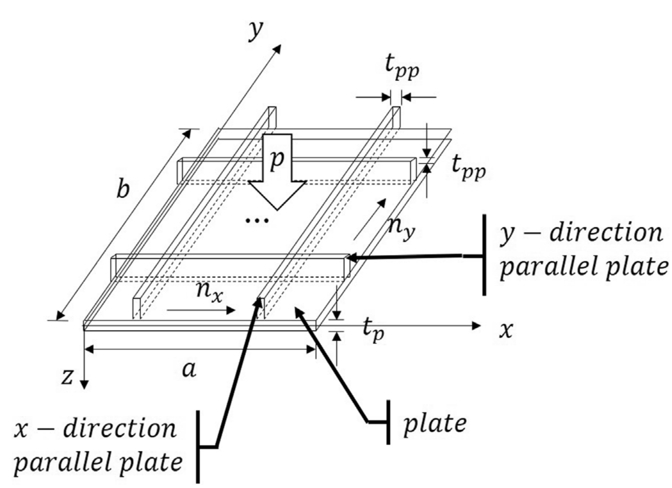

Fig. 1. Dimensions of the parallel plates.